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HIGH-EFFICIENCY PUSH-PULL MAGNETIC AMPLIFIERS WITH TRANSISTORS AS SWITCHED RECTIFIERS

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MAGNETIC AMPLIFIERS - TECHNICAL REPORT NO. 25

Work Performed Under Office of Naval Research Contract Nonr 760 (09)

High-Efficiency Push-Pull Magnetic Amplifiers with Transistors as Switched Rectifiers

by

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Synopsis

Circuits with duo-directional d.c. output into a single load normally involve considerable power loss in balancing and current-limiting resistors and rectifiers, and typical push-pull efficiencies are less than a theoretical value of 17%. Certain push-pull reset magnetic amplifiers described by Maine however use current-switched rectifiers and offer the possibility of 33% efficiency. The provision of the switching feature is responsible for most of the power loss in the circuit, and the use of transistors as switches in such circuits brings about a considerable improvement in efficiency. In typical experiments the ratio of mean VA in the load to mean VA supply exceeds 60% and the true power efficiency exceeds 80%. The signal may be either d.c. or a.c. depending on the control circuit connection.

The form of output circuit proposed is not limited to reset control action and conventional self-saturating push-pull action with d.c. control is shown to be possible with high efficiency.

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1. INTRODUCTION

In many magnetic amplifiers, push-pull action is used to obtain outputs that depend in polarity (or phase) on the signal polarity (or phase).[1,2,3.]

If polarity-reversing d.c. output is required, series or tee-summing circuits may be used, but considerable power is lost in such networks and the theoretical efficiency has a maximum value of 17%. Improvement is possible if the load has twin windings, since then magnetic summing may be adopted. The effective use of the load winding space is halved by the need for two load windings, only one of which is energized in the full output condition, and therefore the efficiency of magnetic summing is not more than 50%. For d.c. loads where twin load windings are not practical, a bridge configuration has been described that requires twin windings on each core of the amplifier.[1,6,7.] A dummy load is necessary for reset and ballast purposes and this reduces the circuit efficiency to 50% or less. In motor type applications there are difficulties in matching the dummy load to the machine load under varying speed conditions, and a compromise must be made that involves additional sacrifice of efficiency.[6.]

In this paper, various circuits are considered that use transistors as switched rectifiers and efficiencies well in excess of 50% for polarity-reversing d.c. outputs are obtained. A.c. output circuits are not examined, since in general these do not incur the efficiency losses of d.c. output circuits. The circuits on which the work is based are the push-pull voltage-reset (Ramey) amplifiers proposed by Maine, in which the circuit elements are coupled by switched rectifiers that prevent circulating currents from by-passing the load.[4.] A typical full-wave push-pull circuit is shown in Fig. 1A and this has input/output characteristics as in Fig. 1B and 1C. With a d.c. signal of one polarity cores 1 and 4 provide output in successive half-cycles while cores 2 and 3 are "passive"; and for the other signal polarity the action interchanges and cores 2 and 3 provide output of reversed polarity. With an a.c. signal, cores 1 and 2 provide a.c. output and 3 and 4 are passive; and reversal of the

signal phase brings about reversal of the core actions and the phase of the a.c. output reverses. The switched rectifiers a, b, c, d in the load side are controlled by bias voltages of gate-supply magnitude acting through resistors R_X equal to the load resistance. This ensures rectifier cut-off for half of each cycle and limits the rectifier current flow to the load current magnitude. With these necessary proportions the switching power for the load circuit is twice the maximum load power, and hence the maximum circuit efficiency is 33% (assuming the power loss in the control side of the circuit to be small).

The concept that suggests itself for the improvement of efficiency in this circuit is the substitution of transistors for the switched rectifiers since the functions of half-cycle cut-off and current limiting can then be performed for the expenditure of much reduced power.

2. PUSH-PULL RESET CIRCUITS WITH TRANSISTORS SWITCHES

In switched operation of a transistor the base-drive current need be only equal to the output current divided by the current gain of the unit, which is normally 10 or more. The base-drive voltage must be sufficient to supply this base current in a typical switching configuration and this is perhaps merely two or three volts. Thus the base-drive power may be only a few percent of the power controlled as a switch.[5] The voltage drop between emitter and collector when acting as a closed switch may be 0.3-1.0 volt at full load current depending on the transistor type and the amount of drive provided. The total switch loss therefore is unlikely to exceed 5% of the power switched in a correctly proportioned circuit.

The rectifiers a, b, c, d of Fig. 1A may be replaced by transistor switches as shown in Fig. 2A. Then for 5% switch-loss per pair of transistors the theoretical maximum efficiency of Fig. 2A should be about 90% compared with 33% for the earlier circuit. Other losses to be allowed for include winding resistance losses and normal rectifier forward-voltage losses, and those may amount to 10 to 20% depending on the design proportions. The

power supplied to the control circuit for flux reset is normally small, but should be allowed for in assessing efficiency.

The circuit of Fig. 2A may be re-arranged to use pnp and npn units in complementary symmetry, Fig. 2B, which allows base-drive to be obtained from the gate-voltage windings thus simplifying the supply transformers. In Fig. 2B transistors switches are shown also in the control side of the circuits, although the power levels there are low and the effect on efficiency correspondingly small.

The circuit of Fig. 2(A) gives reversing-polarity d.c. output for a d.c. signal and reversing-phase a.c. output for an a.c. signal input. Rearrangement of the control circuit as shown in Fig. 3 interchanges the control action so that a d.c. signal gives a.c. output and vice versa. Although only full-wave circuits are given the same principles apply to half-wave versions of these circuits.[4]

Since the circuits are constructed from voltage-reset (Ramey) type configurations the transient response to be expected is merely the half-cycle delay of such arrangements.

The switch-off condition for a pnp transistor is that the base must be positive with respect to both of the other electrodes. Thus the magnitude of the switch-off voltage between the emitter and the base limits the voltage that can be sustained with the collector positive with respect to the emitter.[5] This is the reason for the inclusion of diode rectifiers in series with each transistor, and the possibility exists of eliminating the diodes if the base switching voltage can be made larger.

3. EXPERIMENTAL EXAMINATION OF THE NEW PUSH-PULL RESET CIRCUITS

An experimental examination was made to establish that the full-wave circuits of Fig. 2 and Fig. 3 functioned as expected and gave high efficiency. Four cores of Orthonol of 2-1/4" I.D., 3-1/2" O.D. and 3/4" tape width were provided with gate windings of 500 turns and control windings of

166 turns. At 60 c/s the gate winding saturation voltage per core was just over 50 volts (rms). In these push-pull circuits, triggering of an active core produces voltage across the load which adds to the gate voltage supply of the passive section of the amplifier and therefore the gate voltage rating in push-pull must be half that for normal single-ended operation. In these experiments the gate voltage of each half of the circuit was therefore set at 25 volts. The power transistors available were 2N68 units, and these were selected to have collector-emitter turn-over voltages in excess of 60 volts when the base was positive with respect to the emitter. For the circuit of Fig. 2B, npn transistors are also required and type 2N95 units were used.

Examination of the circuit waveforms confirmed the expected action and the improvement in efficiency. A typical characteristic for the circuit of Fig. 3 for a load resistance of 150 ohms and gate and reset voltages of 25V and 9V, respectively, is given in Fig. 4. The circuit efficiency depends on the output level and increases as this approaches full output. At a signal level of 9 volts, corresponding to almost full output in Fig. 4, the efficiency represented by the load power output divided by the input power was 80%. The need for high-impedance wattmeters to measure true power may be avoided by taking other ratios, such as that of the load current to the total input current, to represent the effectiveness of the push-pull arrangement. For the characteristic of Fig. 4 a load current of 124 mA required an input current to the gate side of 144 mA (mean) and an equivalent of 25 mA to the control circuit side. The ratio of load to input current was therefore 0.76 and the ratio of output - input volt-amperes was 60%. This represents a considerable improvement over values of less than 17% for conventional circuits and the values of less than 33% for switched rectifier circuits.

For these experiments the amplifier elements were designed to be of negligible winding resistance to facilitate efficiency studies -- the number of turns was low and the input impedance was correspondingly low (about 700 ohms).

This had the effect of limiting the power gain in the experiments - with a load of 150 ohms the gain was about 20 and for a 50 ohms load the gain was about 60. In any practical application the gain could be improved by redesign of the core-elements.

4. PUSH-PULL CENTER-TAP SELF-SATURATING CIRCUIT OF HIGH EFFICIENCY

The voltage-reset (Ramey) amplifiers that have been examined in the high-efficiency push-pull configurations have minimum output for zero signal. Conventional self-saturating amplifier circuits do not have this type of characteristic although by added bias the output at zero signal may be reduced to a low value. The advantage of this condition is that for any given direction of signal two cores of the push-pull configuration do not contribute to the output and therefore the fluxes do not saturate and thereby open up circuit paths through which circulating current may by-pass the load. With this consideration in mind it was decided to examine the transistor technique of push-pull coupling with conventional self-saturating circuits suitably biased to be of low standing current at zero control signal current.

The circuit arrangement examined, Fig. 5A, is identical on the load side to the configurations (Fig. 2A and 3) already discussed. On the control side the bias and signal circuit connections are such that cores 1 and 4 may be regarded as forming a center-tap, self-saturating circuit acting in push-pull with a similar configuration formed by cores 2 and 3. In Fig. 5B the full-line curve is a typical push-pull characteristic and the dotted line represents the output obtained from cores 1 and 4, with the other cores disconnected to show the extent of the bias provided. The gate voltage was 25 volts and loads in the range 150 to 50 ohms were used. For a load current of 290 mA in 50 ohms the total input current to the circuit was 325 mA (mean). This represents a volt-ampere output/input ratio of 0.52, which is very much better than for conventional series or tee-summing networks.

With Orthonol cores as described in Section 3, there was a tendency for looping of the characteristic to occur at low signal levels. Triggering is a well-known effect in this class of core material, but to confirm that the circuits were not responsible the experiments were repeated with 4-79 Mo-permalloy cores and the effect was absent. Inspection of the wave-forms for both types of material showed that the reverse voltages across rectifiers and transistors might reach about twice the peak value of the 25 volt (rms) gate voltage.

Some consideration was given to the possibility of applying the technique to a pair of bridge self-saturated circuits and the conclusion was reached that eight transistors would be required but that the voltage rating would be half that for the center-tap configuration. Since the number of transistors involved seemed rather great for the circuit function the matter was not further examined.

Transient response measurements were made for the center-tap push-pull self-saturated circuit and it was found that the response in the region of zero signal was adversely affected by dead-time effects that tend to occur in self-saturated units biased to minimum output. Therefore if fast response is required the use of the voltage-reset configurations described in Section 3 is indicated.

A few tests with inductive loads showed that it was necessary to compensate for the inductance by a capacitor-resistor circuit in parallel with the load, otherwise bistable characteristics occurred and circulating currents could flow between the push-pull units.

5. DISCUSSION

By the use of transistor switches, push-pull reset magnetic amplifiers may be increased in efficiency to appreciably more than 50%. The same technique may be applied to center-tap self-saturating connections with improvements of volt-ampere output/input ratios by a factor of three or more.

Four transistors are required for full- wave push-pull circuit action and these must be rated at about twice the peak applied gate-voltage. This voltage rating requirement constitutes at present a limitation on the applicability of the technique. The power dissipation in the transistors is small and temperature effects on linear parameter are not important since switched action is used.

In many magnetic amplifier applications the low volt-ampere efficiency of conventional push-pull configurations is not important. In certain military applications, however, the power supply available is limited and excess current demand must be avoided to conserve power and to restrict unnecessary heat generation that may present dissipation problems. With a limited power supply the source impedance is usually appreciable and excess current demand may cause deterioration of supply voltage wave-form and therefore adverse coupling interaction between independent circuits operating from the same source. In such circumstances the high-efficiency push-pull magnetic amplifier circuits proposed may well be found of value.

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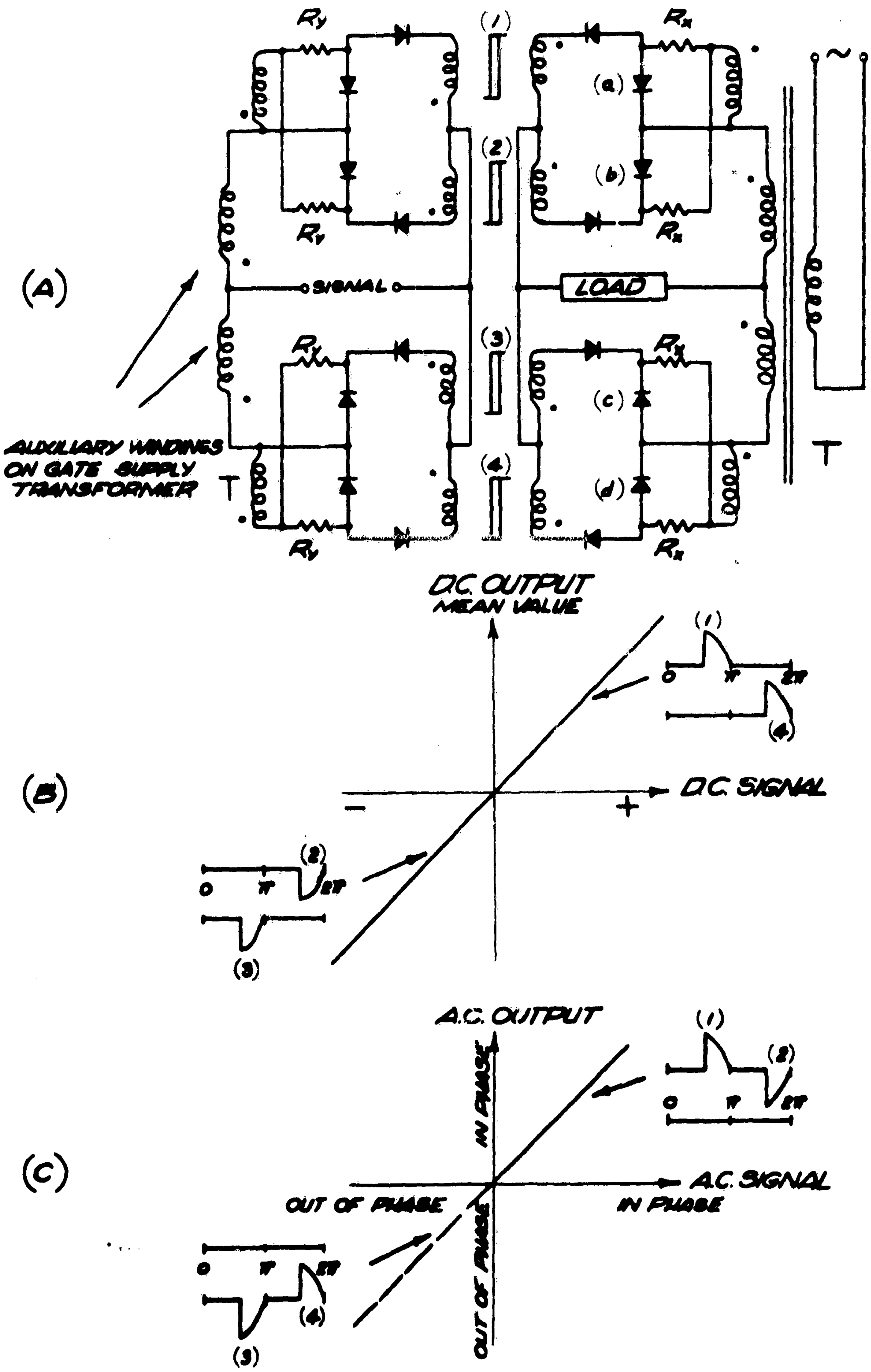
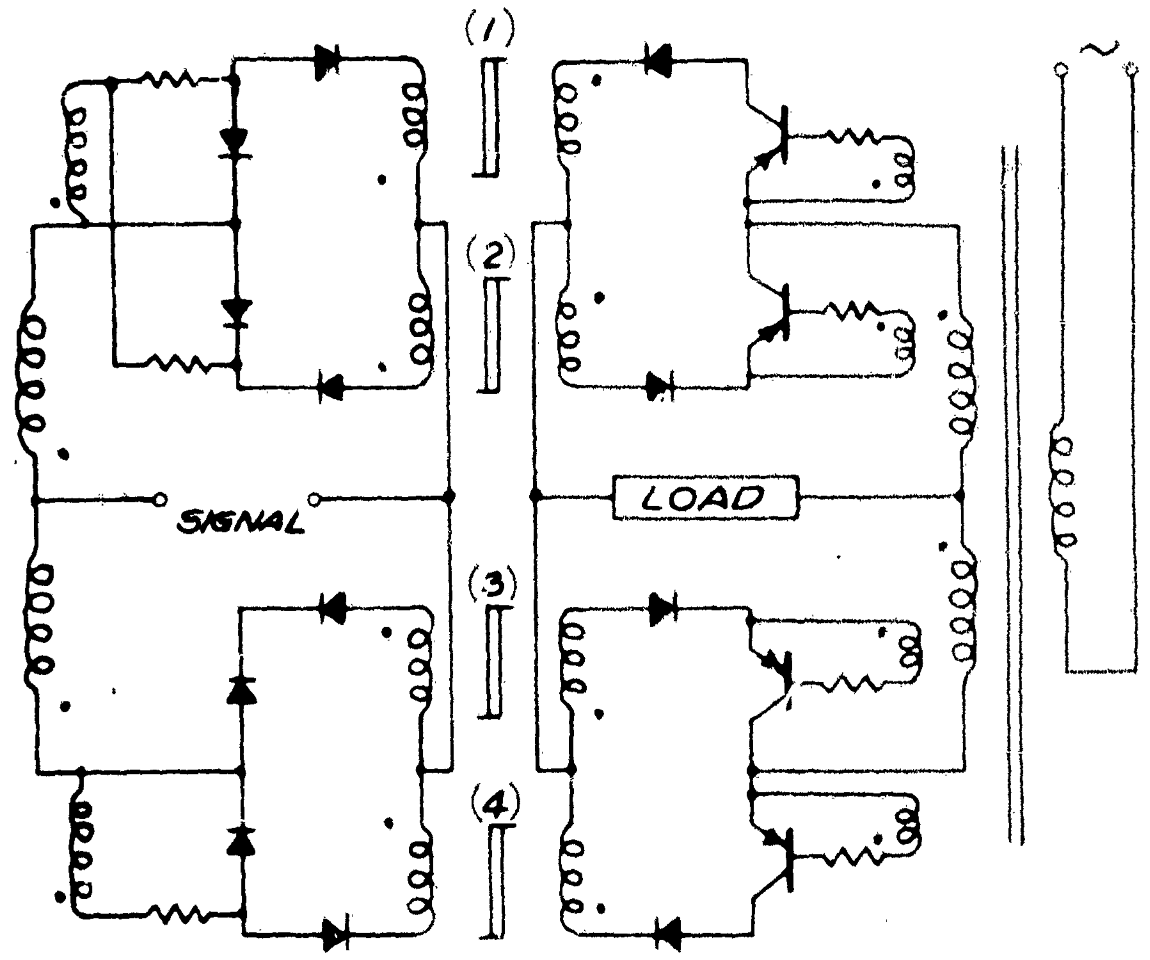


Fig. 1 - Push-pull reset magnetic amplifier with switched rectifiers giving D.C./D.C. or A.C./A.C. characteristics.
(A) Full wave circuit (Maine)
(B) Action with D.C. Signal
(C) Action with A.C. Signal

(A)



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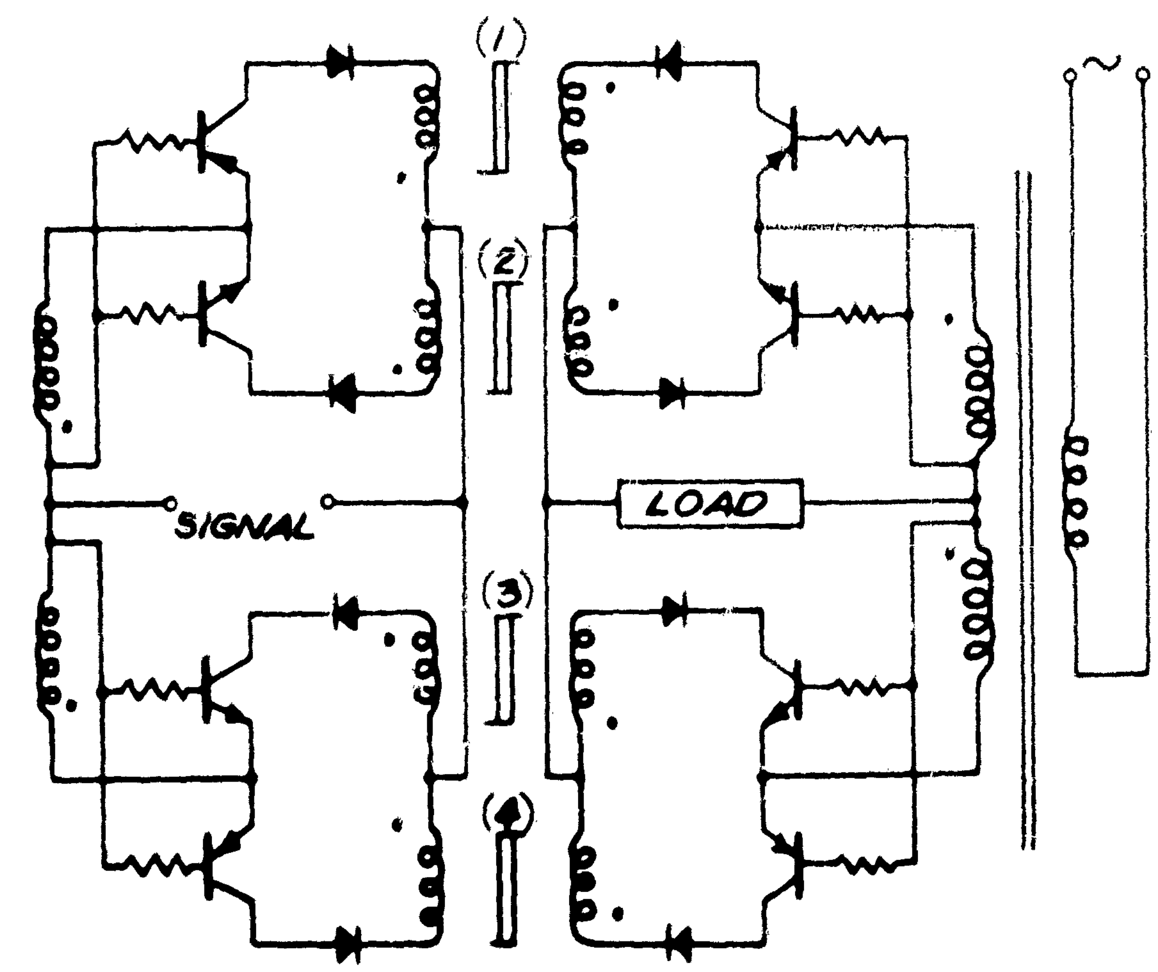

Fig. 2 - Push-pull reset magnetic amplifiers with switched transistors.
(A) Switched rectifiers in load side of Fig. 1 replaced by transistors
(B) With trans'stors in both the control and the load sides

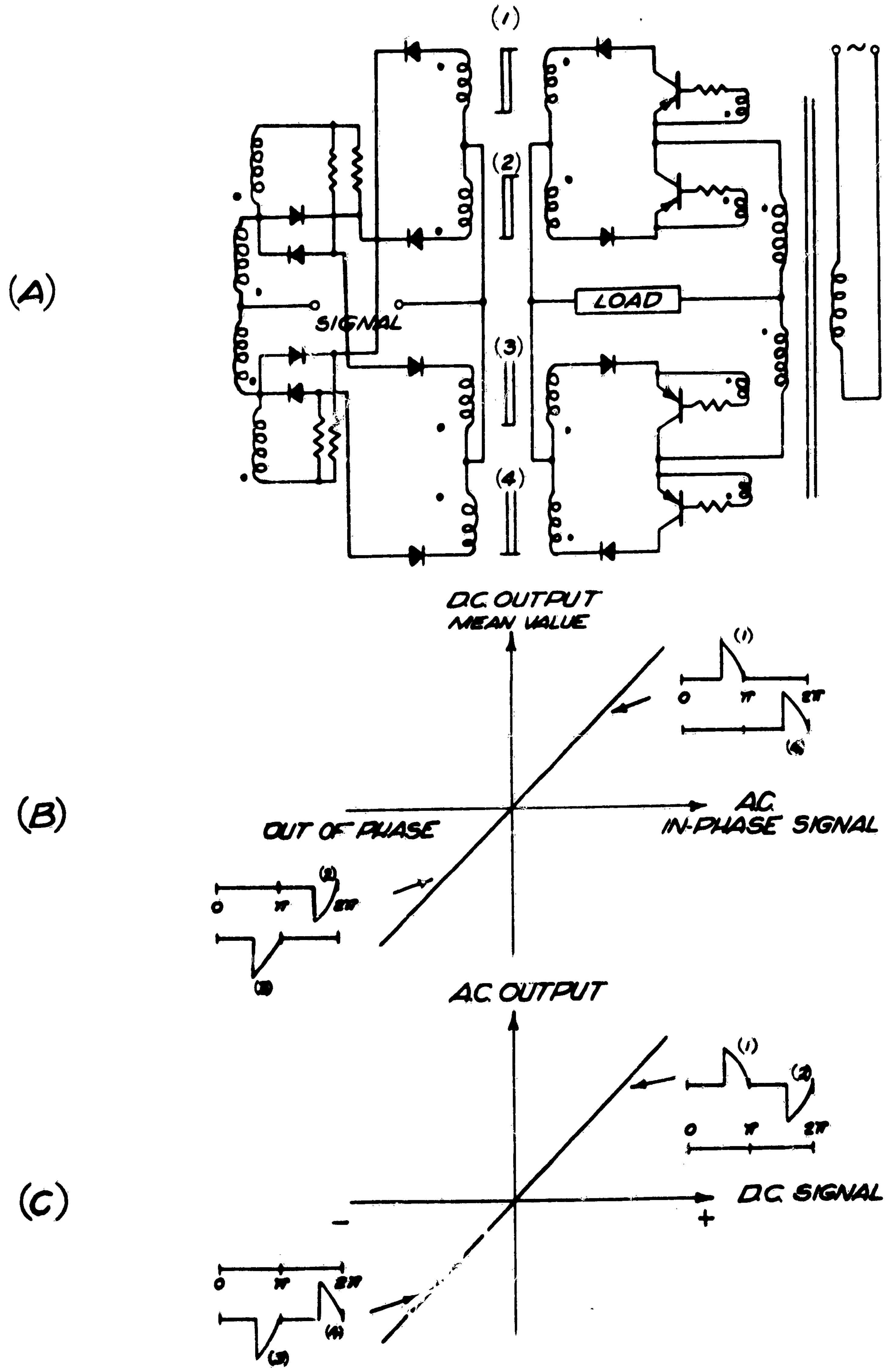

Fig. 3 - Push-pull reset amplifier with transistors and with the control circuit arranged for D.C./A.C. or A.C./D.C. characteristics
(A) Circuit - compare the control side with Fig. 2A
(B) Action with A.C. Signal
(C) Action with D.C. Signal

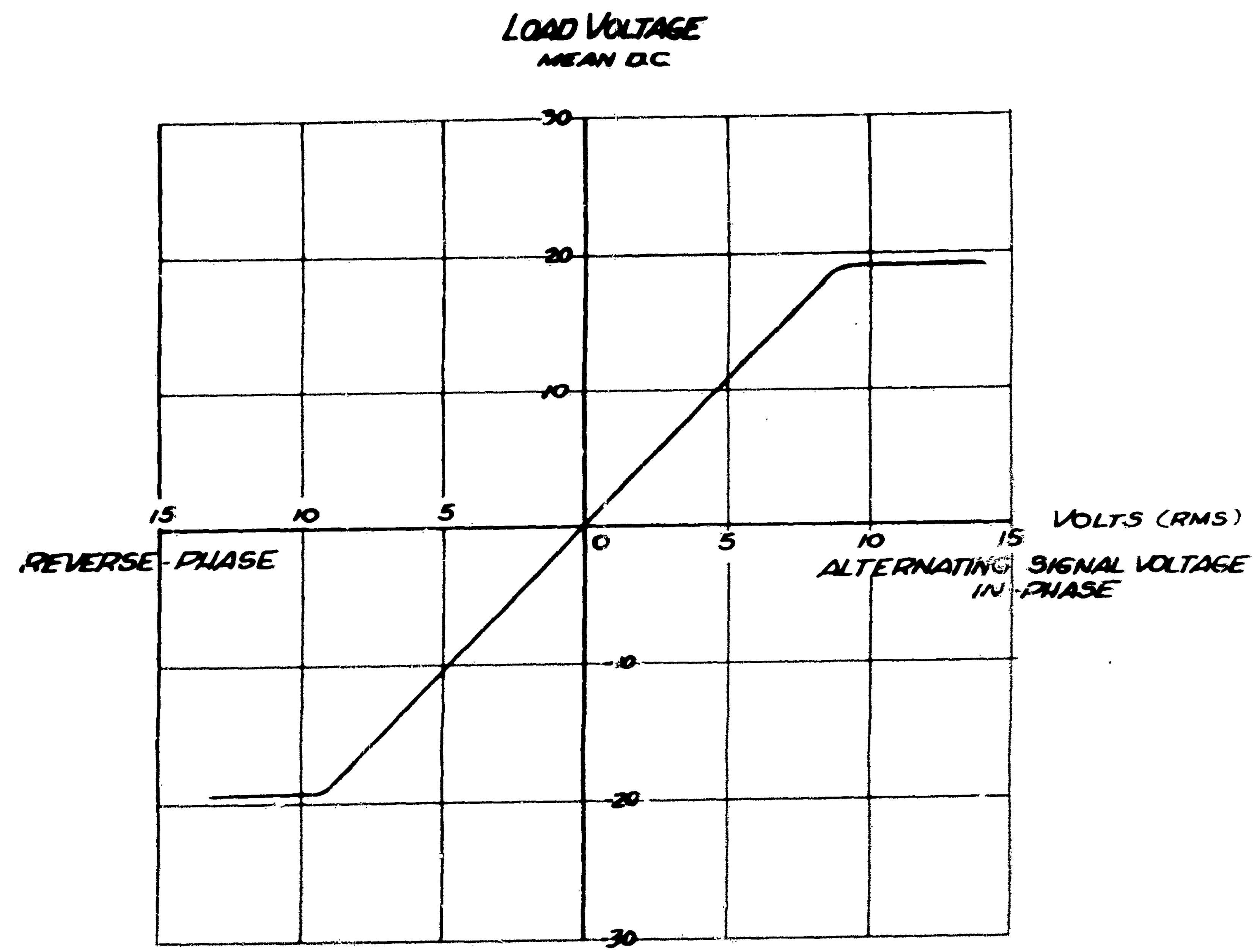

Fig. 4 - Typical experimental output characteristic for the circuit arrangement of Fig. 3.

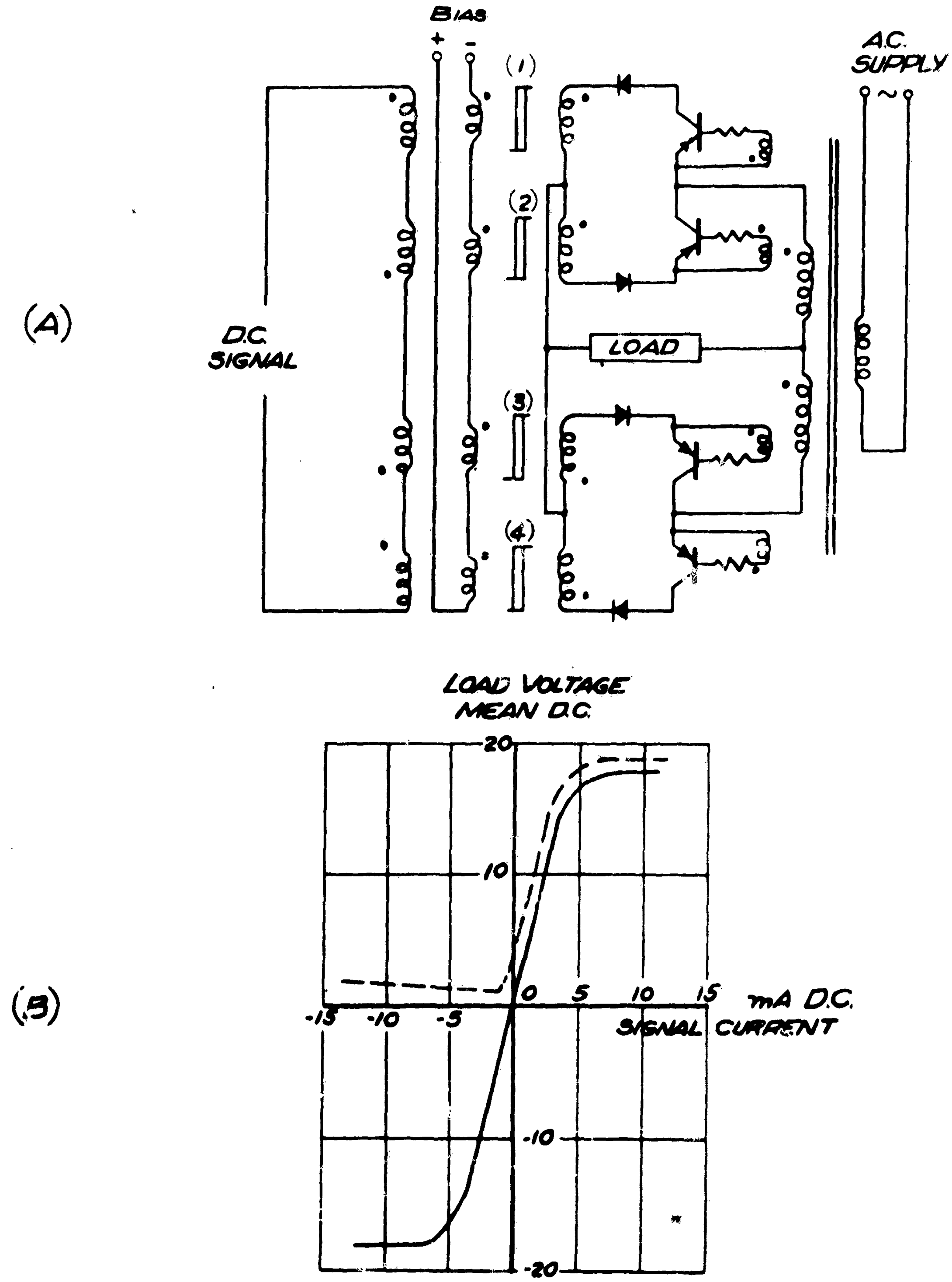

Fig. 5 - Push-pull self-saturating amplifier with switched transistors.
(A) Circuit of push-pull center-tap amplifier
(B) Experimental output characteristics